Trends in

Applied Sciences Research

ISSN 1819-3579

Academic
Journals Inc.

www.academicjournals.com

Trends in Applied Sciences Research 7 (1): 87-95, 2012
ISSN 1819-3579 / DOI: 10.3923/tasr.2012.87.95
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Detection of Partial Discharge Location in Power Generator Windings by Means of Frequency Response Analysis

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ABSTRACT

Frequency Response Analysis (FRA) is one of the comparative methods which can help to assess the condition of insulation in high voltage equipments. The large power generators have parallel connected coils with much fewer but longer turns. Since, the coils lie in the slots, they have considerable capacitance to grounded slot's walls. Also, the conductors have negligible mutual inductances to each other. In this study, the ladder-network of generator winding has been modeled, then effect of its parameters which may change during the operation has been studied and simulated base on winding transfer function. For this purpose, the simulation has been performed with a power generator in PSpice software which is suitable for frequency domain analysis. Then, a PD signal injected in several points of winding model and its frequency response has been measured in different points. Measured results from different locations in frequency domain show that FRA could be use as a comparative method to discriminate the origin of PD signal and so, PD propagation will be observed in generator windings.

Key words: Frequency response analysis, ladder-network, partial discharge propagation, power generator

INTRODUCTION

Power generators are one of the important and expensive equipments in power network which produce electrical energy. So, an unexpected defect could cause interruption in the network and made a lot of costly problems. So, condition monitoring and maintenance should be examined regularly during their life time. Power generator includes many parts that winding should be considered as one of its important components. Since generator winding conductors are carrying high current and also, are under potential, they should have certain characteristics. Because these instances (current and voltage) in addition to make electrical stress, force thermal stress on insulation and lead to premature fatigue and exhaustion. Noteworthy point is that other stresses such as mechanical stress and vibration problems will be effective in increasing the speed of premature aging of the insulations. In addition, numerous statistics and experimental tests show that most faults of generator occur in their winding insulations (Shaozhen and Birlasekaran, 2006). Therefore, it is necessary to diagnose and maintain the insulation defects for providing electrical energy with high reliability and preventing unpredicted outage of power generators.

Since 1960, many researches have shown that the presence of PD phenomenon in electrical equipments is the prominent indicator for the assessment of insulation deterioration. The cause of the deterioration can be due to mechanical, thermal, electrical and/or environmental factors

(Gross, 2002). The PD phenomenon is movement of electrons combined with small sparks that occur in the insulation of electrical equipments such as switches, cables, transformers winding, motors and power generators. Incidence of PD is one of symptoms of primary defect and fatigue in electrical equipments which should be duly recognized. Each PD can be occurs because of inordinate electrical stress on insulation. Air cavity, moisture and impurities in insulation cause increase in PD intensity which can lead to breakdown of electrical insulation, ultimately (Wilson, 2004).

Various diagnosis methods such as those based on the monitoring of temperature, flux, ozone, vibration and PD measurement using Radio-frequency (RF) couplers, including resistance temperature detector, stator slot coupler, a High Frequency Current Transformer (HFCT) and capacitive and ultrasonic probes for a power generator have been reported (Stone, 2002). PD measurement can be performed continuous or discrete and detected online or offline during the operation. By comparing these measurements results with primary safe state, it could be determined whether that the tested equipments require maintenance or not. Interpretation of PD data can even determine the remaining life, loading condition and also be impressive in diagnosing the fault location (Wilson, 2004).

PD-source identification and characterization is an important research area in electrical equipment insulator monitoring. Being small and including noise is the main difficulty in PD signal analysis (Mortazavi and Shahrtash, 2008). Different techniques to eliminate noise based on the difference of pulse arrival time from two bus couplers (Stone, 2002; Zhu and Green, 1998), pulse-by-pulse noise rejection methods using multiple sensors and deionizing method using wavelets have been introduced (Mortazavi and Shahrtash, 2008; Ma *et al.*, 2002). As the attenuation and frequency content on the propagated PD and noise signals are different, after deionizing, the type of developing PDs are identified using the hybrid clustering methods, phase-resolved PD patterns, PD magnitude/number distribution, PD trend analysis and etc., with single PD, propagation and attenuation characteristics at different electrical length are extensively evaluated to identify the location of PD (Gulski and Kreuger, 1992; Wang and Zhu, 1998). In addition, simulation based studies have been done to recognize PD origin in power network, too (Shaozhen and Birlasekaran, 2006; Ming *et al.*, 2005).

In this study, propagation and origin of PD in power generator winding has been considered based on simulation. For this purpose, electrical model of generator winding has been explored. Therefore frequency response analysis has been performed using PSpice software which is suitable for frequency analysis purpose and there was seen some resonance due to inductance and capacitance of the winding model. These resonances could be shown by poles and zeroes in winding transfer function. Therefore, the effect of changes in parameters of model and the number of division in ladder network has been investigated by Frequency Response Analysis. Finally, a PD signal has been injected at different points of ladder-network model and the results have been measured at various location of model and have been considered in time and frequency domain together. These simulation results prove the significant role of FRA as a dominant method to locate the PD origin and its propagation.

CIRCUIT MODELING OF POWER GENERATOR WINDING

Power generators due to their low voltage and high power have parallel connected coils with much fewer turns. In this part, to simulate the generator winding and study PD propagation, it is necessary to model the coil and its insulation. Thus, each phase of the generator is modeled

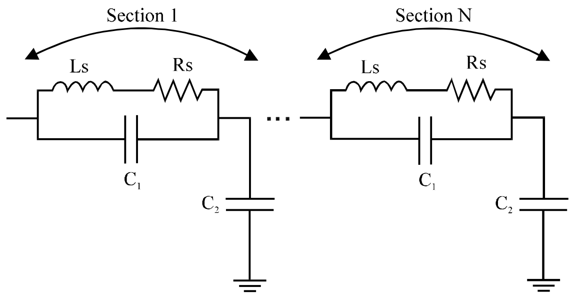

Fig. 1: Circuit model of N turn of winding of generator stator

Table 1: Studied generator winding parameters

Description	Value
Rated Power (MVA)	250
Rated Voltage (KV)	16.5
Winding Inductance Ls (μH)	0.33
Winding Resistance Rs (Ω)	0.48
Winding Capacitance C1 (nF)	4.5
Capacitance between Winding and Generator Wall C2 (nF)	22.8

as a transmission line ladder network. Each coil is represented with RS, LS, C1 and C2 which are the conductor resistance, conductor inductance, coupling capacitance between turns and to the generator grounded wall, respectively (Shaozhen and Birlasekaran, 2006). Hence, with multi turns, the explored circuit can be duplicated into N-section as shown in Fig. 1.

EVALUATION EFFECTIVE FACTORS ON GENERATOR'S WINDING MODEL FREQUENCY RESPONSE

The model in Fig. 1 has been used for simulating and studying the effect of impedance and capacitance of a generator winding. Simulation has been done using PSpice software and the results have been interpreted below. The winding parameters of studied generator have been tabulated in Table 1 (Shaozhen and Birlasekaran, 2006; Ming *et al.*, 2005).

Number of model divisions' effect on frequency response characteristic: In this section, the generator's winding model has been considered in 3 cases, first with N = 4 sections, second with N = 6 sections and at last with N = 9 sections. The results in Fig. 3 show that the resonances numbers will be increased by rising N.

Increasing sections of a model causes to smaller division that constricts the area under considered location of the PD origin, so the accuracy of PD origin locating will be increased.

It should be noted that the values of Table 1 are for whole generator winding, so, to obtain the values for each section it would be divided into sections Numbers (N). In continue the analysis of parameters have been performed by a model with six sections that has been shown in Fig. 2. Table 2 shows the parameters of winding model for six sections.

Effect of resistance and inductance of winding on FRA characteristics: Since deformation or short circuits in coils, change the resistance or inductance value of winding, thus these defects can be shown in frequency response by changing the resonance peak and its frequency. On the

Table 2: Studied generator's winding parameters for one section out of 6

Description	Value
Winding Inductance Ls (μH)	0.055
Winding Resistance Rs (Ω)	0.08
Winding Capacitance C1 (nF)	0.75
Capacitance between Winding and Generator Wall C2 (nF)	3.8

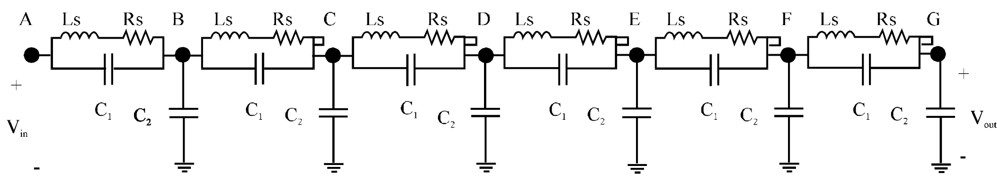

Fig. 2: Ladder network model of generator winding with six sections

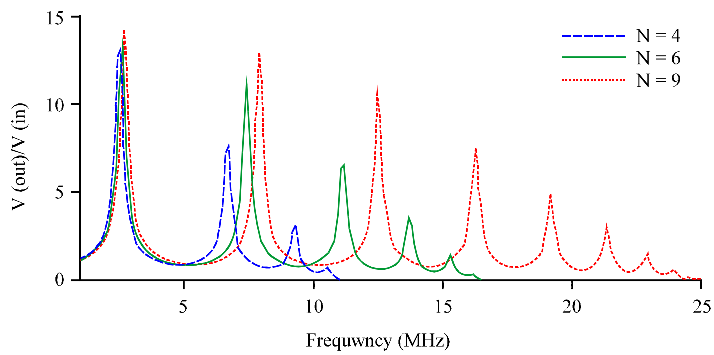

Fig. 3: Frequency response analysis of power generator's winding model with N = 4, 6 and 9

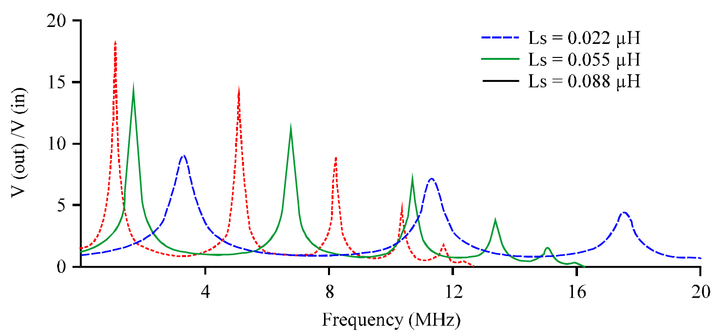

Fig. 4: Effect of Ls

other hand, by comparing the generator winding frequency response in healthy and failure mode, the defects can be discovered. Figure 4 shows the results of inductance changing on transfer function.

In Fig. 4, three curves are observed, one related to LS = 0.055 μH is the normal and two other curves has been obtained by increasing LS to 0.088 μH and decreasing to LS = 0.011 μH. As the frequency response indicates in Fig. 4, by increasing in LS value, first peak of each curve will occur in lower frequency. The following equation can prove this fact. The velocity of wave has reverse

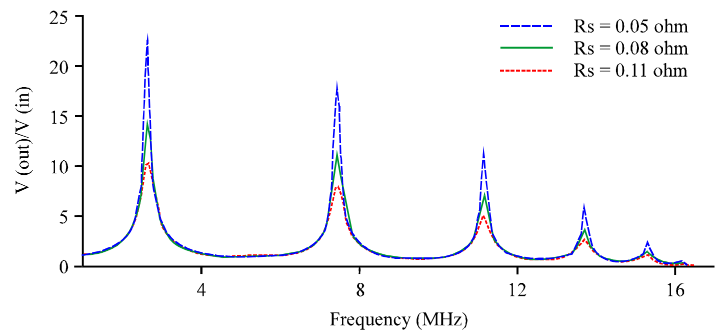

Fig. 5: Effect of RS

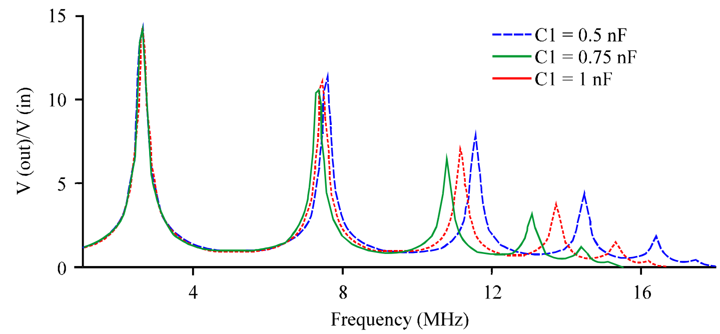

Fig. 6: Effect of C1

proportion with the inductance and capacitance. It means that the minimum LS have more velocity so it starts early in time and the frequency of firs peak will be more than others. Another characteristic is the peak magnitude which reduced by decreasing in LS:

$$v = \sqrt{\frac{1}{LC}} \tag{1}$$

After that, the effect of resistance on frequency response has been simulated. So, the RS has been changed from 0.08 Ω in normal state to 0.05 Ω and 0.11 Ω. Figure 5 shows that only the magnitude of peaks changed by different RS.

Effect of winding capacitance to each other and to generator grounded wall on frequency response characteristic: Displacement, moisture or insulator aging could change the capacitance value in winding model. These cases have been simulated in electrical model by changing in C1 and C2. Simulation has been performed by three values as 0. 5, 0.75 and 1 nF. The results in Fig. 6 shows increasing the amount of C1, causes attenuation in low frequency and resonance will occur in closer frequencies. It means there are more time intervals between resonances. It is obvious from Fig. 6 that C1 doesn't play an effective role in velocity.

Another study has been performed by changing amount of C2, from 2.5 to 3.8 nF and 5.1 nF. Simulation results in frequency-domain have been shown in Fig. 7. It is seen that the resonance

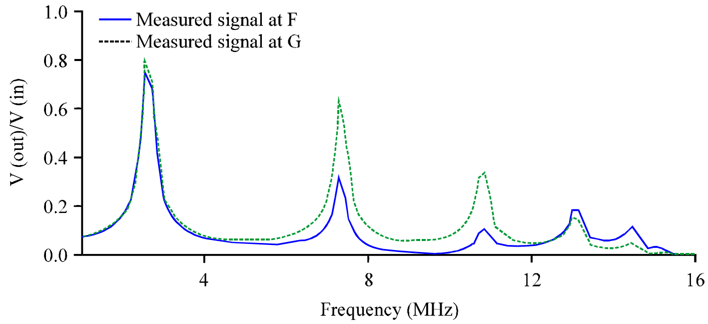

Fig. 7: Measured PD signal at F, G in frequency domain

Table 3: PD pulse characteristics

Description	Value
Pulse Magnitude (v)	25.0
Pulse Start Time (mSec)	0.5
Pulse Rise Time (nSec)	2.0
Pulse Fall Time (nSec)	15.0

bandwidth will increase by higher values of C2 and first resonance occur in low frequency. These simulation results prove that the winding parameters affect on frequency response of model. Thus, FRA can be used as a strong tool to compare different states (healthy, faulty, aging and etc.) of a winding and can diagnose displacement or deformation in a generator winding.

The study of PD propagation and its origin in generator winding using FRA: The PD phenomenon is passing of electrons combined with fast small sparks which can carry high or low energy due to its intensity. This phenomenon occurs in insulations of electrical equipments due to aggression of limited voltage.

At first, to predict PD origin in generator winding, the PD propagation has been studied. So, a high frequency pulse with certain characteristics, shown in Table 3, has been injected in ladder network model. Also, results have been obtained by simulation in PSpice with both time and frequency domains.

Simulation of PD propagation: To show the PD propagation, the PD signal has been injected at point A in ladder-network model in Fig. 3. The measured data from points F and G have been shown in Fig. 7 and 8 in frequency and time domain, respectively. It is obvious from Fig. 7 that the bandwidth and peak magnitude decrease by going far away from the PD origin. By zooming in Fig. 8, it could be seen that the distortion made by PD has been started at 515 nSec at point F and 525 nSec at point G. This result proves the motion and propagation of PD signal along the generator winding.

To evaluate the propagation, PD signal has been injected at point A, B, C, D, E, F and output has been measured at point G which has been shown in Fig 9. The results show if the measuring node approaches to PD signal injection location, the curves will move during the frequency and their first resonance occurs in higher frequency. These results can be used to diagnose the PD origin in generator winding.

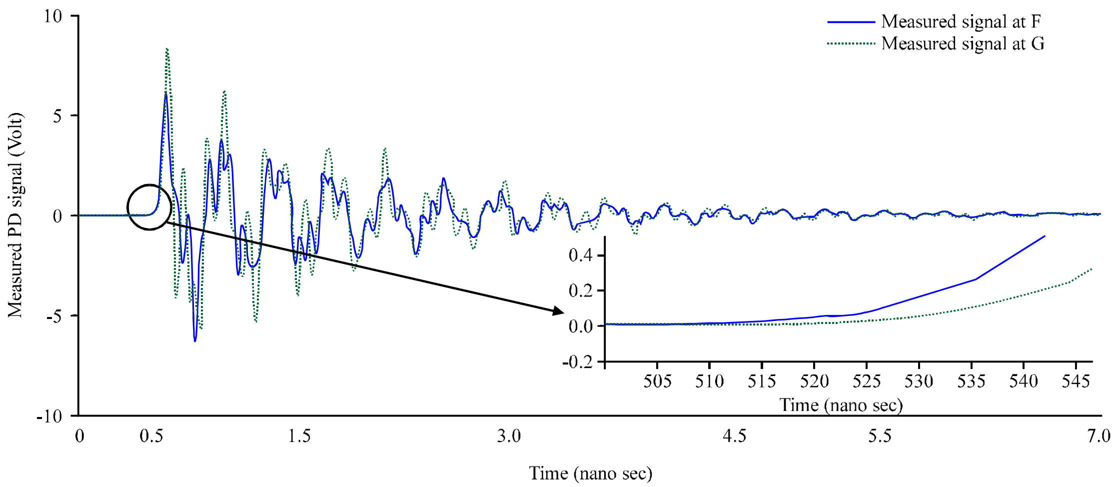

Fig. 8: Measured PD signal at F, G in time domain

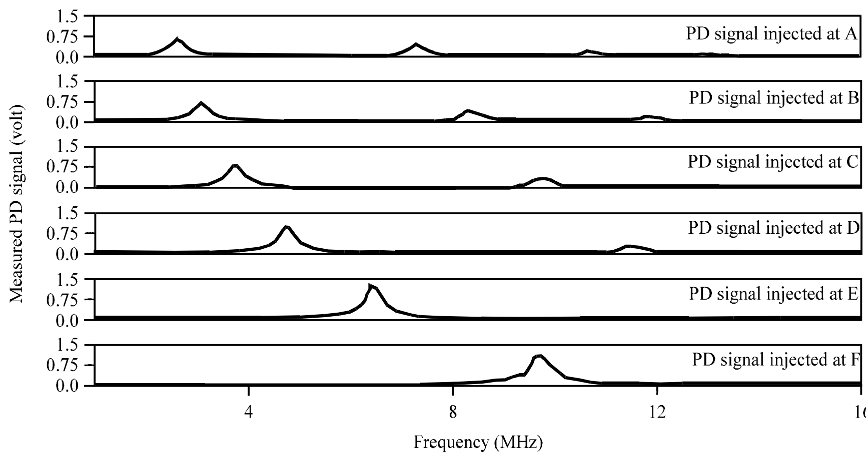

Fig. 9: Measured PD signal at G

Predicting the PD origin: Partial discharge can occur due to electrical stress at any point of generator winding. By comparing measured data at terminals F and G, time interval of 10 nSec shows the propagation of PD signal due to distance between injection node and measurement terminal.

Figure 9 shows measured signals in frequency domain. It has been observed that closer injected PD signal has first peak with higher frequency. In other hand, measured results at B, C, D, E, F, G of PD signal injected at terminal A has been shown in Fig. 10.

It is obvious that the bandwidth and magnitude of first resonance decrease because of nearing the measuring point to PD origin. Simulated results in time domain (Fig. 11) shows the propagation of PD signal during the time. So, the first peak of closer measuring nodes to PD origin will appear in earlier time. So, the terminal B is nearest point to PD origin.

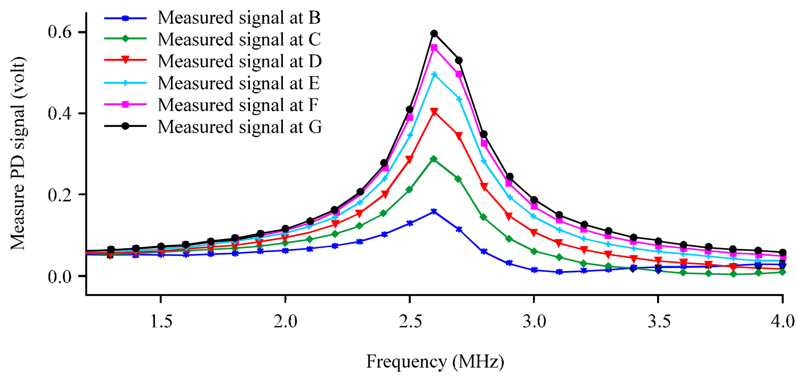

Fig. 10: Measured PD signal at B, C, D, E, F in frequency domain

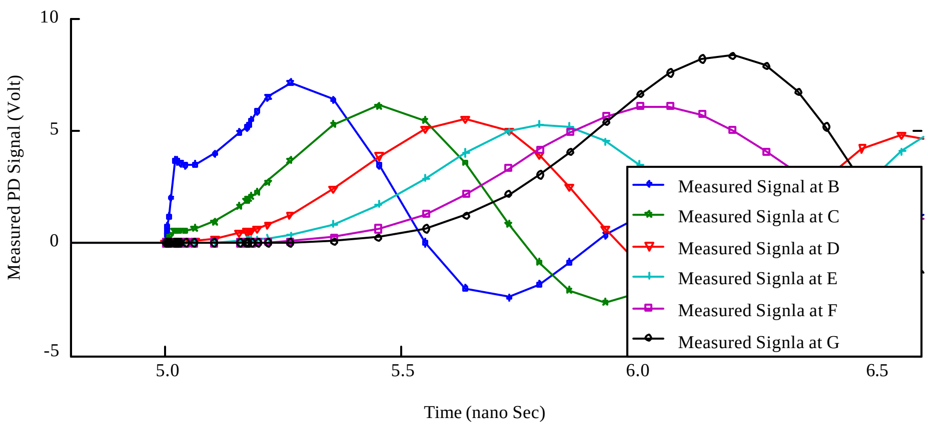

Fig. 11: Measured PD signal at B, C, D, E, F in time domain

CONCLUSION

In this study, the ladder network model of generator winding has been simulated in PSpice which is appropriate for frequency domain analysis. Then the effects of its parameters have been studied on frequency domain. So, a PD signal has been injected at many terminals of model and output signal has been measured in different points. In this study, the results have been considered in both time and frequency domains. The simulation results show if the PD occurs close to the measured node, measured signals appears in lower time and higher frequency and its magnitude will be low in frequency domain. These facts prove that FRA can be a good method to diagnose the problems like insulator defects, corona and compare with primary state when the equipment is healthy and nearly to first use.

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